INDUSTRIAL PHOTOGRAMMETRY APPLIED TO DEFORMATION MEASUREMENT

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ABSTRACT

Industrial photogrammetry is nowadays being applied for the monitoring of structural deformation. This paper briefly overviews the basic types of deformation measurement networks and touches upon aspects of deformation analysis. Four recently conducted deformation measurements which utilized high-precision photogrammetry are then reviewed. The applications consist of periodic inspection of an assembly tool, and deformation measurements of a large parabolic antenna, an age-forming mold for aircraft wings and a large process compressor.

INTRODUCTION

Over the past half decade or so close-range photogrammetry has become firmly established as a precise measuring tool for industrial metrology. As well as finding application in general structural measurement, photogrammetry is nowadays being applied to deformation monitoring. In this paper four recently conducted deformation monitoring projects are reviewed. The aim of the paper is simply to highlight to the reader the capabilities and numerous advantages offered by photogrammetry for industrial deformation measurement.

COOPER (1984) has reviewed four different photogrammetric approaches for deformation measurement, namely (a) the time parallax method, (b) controlled stereomodels, (c) the resection/intersection procedure and (d) the bundle adjustment approach. Of these methods only the latter is well suited to yielding the high accuracies sought in industry, and here the discussion is confined to the photogrammetric bundle adjustment approach. A feature of this data reduction method is that rigorous statistical testing techniques can be applied in subsequent deformation analyses.

Of importance in deformation monitoring is an a priori expectation of the likely behaviour of the object being measured. The subsequent analysis approach may differ depending on whether the aim of the measurement is to establish the change in shape of a body which is expected to deform, or to determine if deformation has occurred in an object which is assumed to be stable. The emphasis in the former situation is usually on a description or modelling of the deformation, whereas in the latter case one is often involved in ensuring that measured point displacements are indeed indicators of a shape change and not the result of random or systematic errors in the photogrammetric network. Of the four measurements reviewed in this paper, three, namely a large microwave antenna, an age forming tool for aircraft wing 'skins' and a sizable industrial process compressor, fit into the category of anticipated deformation, whereas one, a wing assembly tool for a fighter aircraft, belongs more to the case of anticipated stability.

Two basic types of three-dimensional networks (be they photogrammetric or geodetic) used for monitoring displacements and shape changes of deformable bodies can be distinguished (e.g. HECK, 1982):

i) relative deformation networks in which all monitoring points are assumed subject to movement, and
ii) absolute deformation networks in which a given subset of the monitoring points are assumed to be stable.

In the absolute case the deformation analysis procedure is assisted by the fact that both single point displacements and localized shape changes can be described in an absolute sense with respect to a stable base. The situation with relative networks is, however, more involved. Here only relative displacements and shape changes of the body can be determined and specialized analysis techniques (e.g. NIEMEIER, 1981; HECK, 1982 and FRASER & GRUENDIG, 1985) are called for in seeking an answer to the question of which point displacements represent statistically significant movements or changes of shape.

In planning a deformation measurement due attention must be paid to the design of the photogrammetric network for each measuring epoch. It is not enough to have a sophisticated deformation analysis procedure if the network does not display the precision and sensitivity required to enable identification of statistically significant deformation at the accuracy level required. A technique termed sensitivity analysis can be utilized to ascertain whether certain deformations will be detectable within the planned network. Sensitivity analysis can be applied via two approaches, that of congruency testing (PELZER, 1972) and that of external reliability (e.g. NIEMEIER, 1982). In a photogrammetric network, sensitivity analysis is normally employed to determine the minimum magnitude of deformations that will be detectable at a given confidence level for a particular network design. An example of sensitivity analysis for a photogrammetric measurement of a landslide area is given in FRASER (1983).

Statistical techniques which are employed in deformation analysis to identify significant point movements or shape changes generally involve the testing of the hypothesis that no deformation has occurred between the measuring epochs. Rejection of this hypothesis indicates that significant relative or absolute point movements have taken place. Two basic steps are normally undertaken in a deformation analysis. In the first step a determination is made, usually via some form of global network congruency testing (e.g. NIEMEIER, 1981), whether in fact the network underwent a deformation. This step, while necessary for monitoring networks of relative type, may be bypassed for absolute deformation measurement networks which contain truly stable reference points relative to which all point movements can be referred. The second step involves a localization in space and time of detectable point movements, and an examination and possible modelling (e.g. via strain analysis where appropriate) of the associated deformation trends. A number of approaches for localization and modelling of deformations have been formulated for use with three-dimensional geodetic networks (see, for example, the review by HECK, 1982), and FRASER & GRUENDIG (1985) have described a deformation localization approach which is quite applicable for industrial photogrammetry.

PRACTICAL APPLICATIONS

In the following sections of this paper four photogrammetric deformation measurements recently conducted by Geodetic Services, Inc. are described. Mathematical aspects of the associated deformation analyses are not detailed; for these aspects and for related theoretical considerations the reader is referred to the literature cited in the references. In reviewing each application, however, an effort is made to relate network design and sensitivity considerations, as well as the deformation analysis approach adopted, to the general concepts outlined above.

Quality Assurance Inspection of Tooling

Within the aerospace industry there is increasing usage of photogrammetry for the periodic inspection of tooling. Photogrammetry offers some significant advantages over the conventional gauging techniques used for quality assurance inspection of tooling (e.g. FRASER and BROWN, 1986). In most tooling applications the deformation measurement type is absolute, since there is virtually always a stable set of master tooling points of known coordinates against which the movement of individual locator points is referred. Stability of the tool is generally assumed, and of critical importance is the localization of single and multiple point movements. A deformation analysis procedure appropriate for the periodic inspection of assembly tooling is as follows:

i) Test the stability of the 'stable' reference point array.
ii) Transform the coordinate system of the two networks being compared into a common reference datum defined by the stable points (in (i) some points may fail the test of stability and these are not included in the datum).
iii) Determine individual movements of the measured tooling points.
iv) Ascertain whether the point displacements constitute a statistically significant deformation, or whether they are a consequence of random measurement error.

With any type of deformation measurement, detection of large monitoring point movements (say greater than 20 times the point positioning accuracy in the photogrammetric network) can be achieved through a simple evaluation of coordinate changes between measuring epochs. With small deformations (say movements of less than 10 times the coordinate standard errors), however, appropriate statistical techniques must be applied to arrive at a correct conclusion regarding the deformation.

In absolute deformation monitoring networks for periodic inspection step (iv) of the analysis procedure above generally boils down to a significance testing of normalized point movements, i.e. one tests the null hypothesis that the displacement divided by its standard error does not represent a significant point movement. Expressed another way, if the displacement vector of a point lies outside the corresponding confidence ellipsoid for that point a significant movement is indicated.

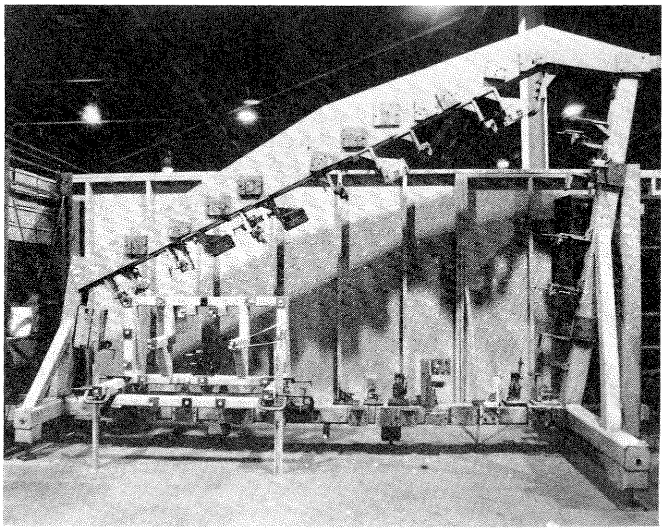


Figure 1: Wing assembly jig with smaller test tool.

As an example of a periodic inspection measurement undertaken by photogrammetry the tool shown in Figure 1 is considered. This 4 x 3m jig is used for the assembly of wing components for a fighter aircraft. Also in the figure is a smaller tool which does not normally occupy the position shown. In piecing together the wing various components are accurately positioned with reference to locator points and surfaces.

The deformation measurement of the wing assembly jig was carried out by GSI as part of a 'benchmark' test. The test was set up to simulate two epochs of inspection. Some 53 retrotargetted points on locators were positioned on both the jig and the smaller tool which was clamped to its base. 'True' coordinates of each point were known but withheld from the participants in the benchmark test, and between the two inspection measurements shim targets, or spacers, were positioned over a subset of the locator points. Participants were required to determine which targets were so adjusted and to measure the thicknesses of the spacers. In the context of the measurement, shim thicknesses represented single point movements due to tool deformation.

The accuracy requirement for the photogrammetric networks was a mean positional standard error of object points of 0.040 mm or better. Higher accuracies would have been readily attainable but the networks were limited to six camera stations in the design process to ensure that a time budget of 2-1/2 manhours could be met for a single inspection measurement (the 2-1/2 hours was from the time of photography to the final output of XYZ coordinates). GSI's STARS system, comprising the CRC-1 camera with 240mm lens, the AutoSet automatic monocomparator and associated data reduction software (see FRASER and BROWN, 1986 for a full system description) was used for the deformation measurement.

At the network design and simulation stage it was ascertained that a convergent imaging configuration of six camera stations would exhibit the required level of sensitivity. The network geometry comprised three camera stations across the front of the tool about 0.5m above the floor, and above each of these positions a station at a height of about 4m. The imaging distance at midfield was close to 6.5m, yielding an image scale of about 1:25.

In the analysis of the results obtained the first step was to evaluate the stability of the reference points. Since the tool was known to be stable during the course of the test measurements this step was used instead to assess the repeatability of the photogrammetric measurement procedure. Once the two networks were brought into a common datum provided by the stable points, coordinate differences were computed. The RMS value of the discrepancies, based on a sample of just under 50 points, was computed as 0.035mm, there being no significant difference between the X, Y and Z axes. This level of discrepancy was consistent with the accuracy of XYZ coordinates obtained in each epoch, namely a mean standard error of 0.03mm, or 1 part in 170,000. Since, in this case, 'true' coordinates (standard errors of about 0.02mm) were also available for the reference points it was possible to evaluate the absolute positioning accuracy of the photogrammetric measurement. Here, an RMS discrepancy value of 0.025mm was obtained.

The next phase of the analysis was to determine single point movements, which in this test case meant shim thicknesses. Of the statistical significance of the point movements there was no question, all spacers had a thickness of 0.4mm or greater. From the measurement of 19 shims an RMS value of 0.028mm was obtained for the discrepancies between the true and photogrammetrically measured thicknesses. All results were within specifications, thus confirming the accuracy and sensitivity of the photogrammetric measurement networks.

Parabolic Antenna

The radio performance of a parabolic microwave antenna is closely related to the degree of conformance of the reflector surface to its geometric design specifications. Surface errors in the antenna can adversely affect gain. Compounding the surface accuracy problem is the fact that large antennas deform under their own weight with changes in elevation angle, and also undergo surface changes due to environmental factors such as temperature and wind loading.

One aspect of a recent photogrammetric measurement of a large antenna in NASA's Deep Space Network was a determination of the deformation experienced by the antenna when its elevation setting is changed from 6 to 45 degrees. This application constituted a relative deformation measurement since changes in shape were anticipated for the entire area of the reflector surface, and there was no stable reference against which to quantify target point movements in an absolute sense.

The antenna measured was DSS-15, a 34m dish situated in the California desert. A photograph of the antenna, showing the cherrypicker which was used to take the photography (of the sub-reflector in this case) is shown in Figure 2. In all, four photogrammetric measurements of the main and sub-reflector were made, as well as supplementary measurements of two of the 2 x 3m panels which make up the reflector surface. Full details of the photogrammetric approach and equipment involved are reported in FRASER (1986). Here the discussion is confined to aspects related to deformation monitoring of the main reflector.

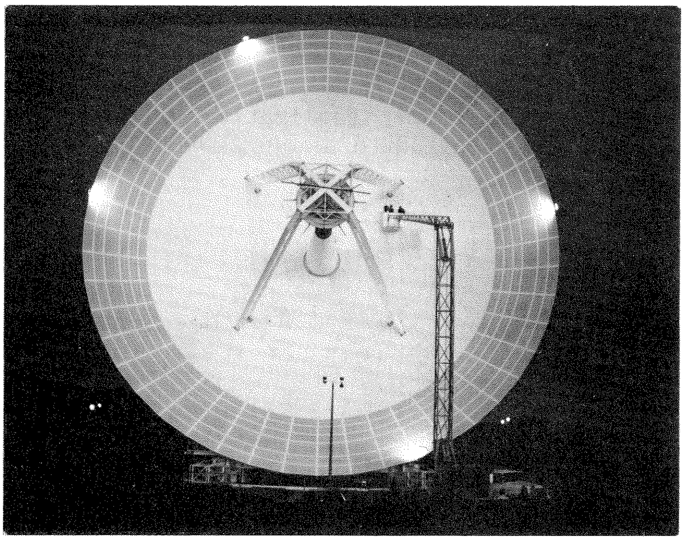


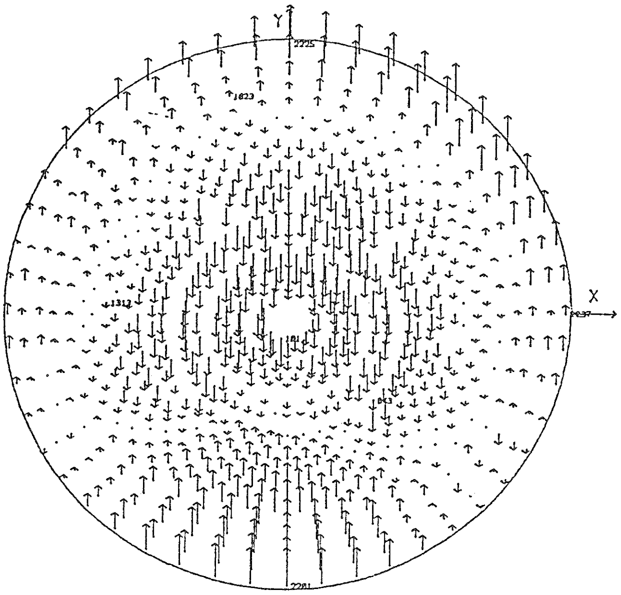
Figure 2: The DSS-15 microwave antenna of 34m diameter.

Basic accuracy requirements for the photogrammetric measurement networks were that an object point coordinate precision (one-sigma, RMS value) of 0.25mm be obtained. To achieve this level of triangulation accuracy in measurements of the antenna at both 6 and 45 degree elevations, convergent imaging configurations of ten and nine camera stations, respectively, were designed. Pre-analysis of these networks indicated that a mean standard error of XYZ object point coordinates of 0.2mm or 1 part in 170,000 of the antenna diameter could be anticipated. This accuracy level was premised on the assumption of an image coordinate measurement standard error of 1.5 micrometers. Such an estimate is moderately conservative for GSI's automatic monocomparator, AutoSet, which displays a digitizing accuracy of about 0.4 micrometers. The camera to be used was a large-format CRC-1 with 240mm lens. Just under 1000 photogrammetric retrotargets were placed as monitoring points on the antenna.

As mentioned, a localization of surface movements was not the main aim of the deformation measurement, and thus a rigorous sensitivity analysis was not called for. Instead, sensitivity was implicitly established through the provision of a high level of network precision and reliability. The scope of the deformation analysis included an examination of the change in shape of the antenna, but perhaps of more importance was the degree to which the reflector conformed to its quasi-paraboloid design at each elevation angle.

In the two photogrammetric networks mean positional standard errors of 0.17mm (1:200,000) and 0.19mm, respectively, were obtained for the 6 and 45 degree settings. An independent check on the photogrammetric measurement results was provided by four shimmed targets on the antenna. The thicknesses of these spacers were determined photogrammetrically by computing the 'height' difference between each shimmed target and the surface at that point. Thus, eight independent measurements of thickness were obtained, providing a mean value for each of the four shims. On comparing the true versus measured thicknesses an RMS error of 0.15mm was obtained, with the range of discrepancies being from 0.02mm to 0.30mm.

The change in shape of the antenna was quantified by determining individual surface point displacements. Since the deformation measurement was of relative type it was first required to bring both photogrammetric networks into a common coordinate reference system through a rigid body transformation. The point movements then computed met the requirement that the sum of squares of the Z-departures (surface changes in the direction of the antenna axis) was a minimum. These Z-departures are shown in Figure 3. Their magnitudes reached a maximum of around 2mm. Note that some other criterion could have equally been applied in the computation of relative deformations in this case. For example, the center portion of the dish could have been assumed 'stable' and thus the depicted movements would have had a mean of zero in the 'stable' area. Flexibility in datum assignment is afforded mainly because a deformation localization was not sought; rather the overall flexing of the dish was required to be quantified.



DSS-15 M-REF Z-CHANGE (HORIZ. - 45 DEG.; 3-D TRANSF.)

Figure 3: Measured point movements on the antenna.

A feature of the photogrammetric calibration of DSS-15 was that both the main and sub-reflectors were measured in a common XYZ coordinate system at the different elevation settings. Targets on the meter long stand-off brackets shown mounted about the sub-reflector rim in Figure 2 provided the 'tie points' between the two networks. Thus, as well as a determination of surface movement of the main reflector it was possible to extend the scope of the deformation measurement to include the determination of the variations in alignment and relative position between the 34m main reflector and the 4m quasi-hyperboloid sub-reflector.

Large Age Forming Tool

Figure 4 shows a 15m age forming tool assembly (mold) which is used to shape wing panels for a large military aircraft. The wing 'skin' is shaped through the application of a vacuum which presses the aluminum panel onto a design surface defined by a series of contour boards. The assembly is then 'baked' in an autoclave at high temperatures to cure (or 'age form') the panel. The tool itself is the largest ever assembled from cast aluminum and it is designed to maintain its shape under both vacuum and thermal loading, as any deformation of the assembly could potentially misshape the skin panel.

To determine the deformation of the tool during the autoclaving process photogrammetric measurements were conducted before and after curing, the two epochs of measurement being separated by seven days. To act as monitoring points 100 retrotargets were placed at critical locations of interest on the tool, as well as on the skin panel itself. Targets occupied positions on the top, sides and ends of the tool. This necessitated a photogrammetric network of 10 camera stations which were evenly distributed around the assembly at a radial distance of 18m and a height above the 'tool' of 12m. The camera employed was again the CRC-1 with 240mm lens, thus giving rise to an image scale of about 1:75.

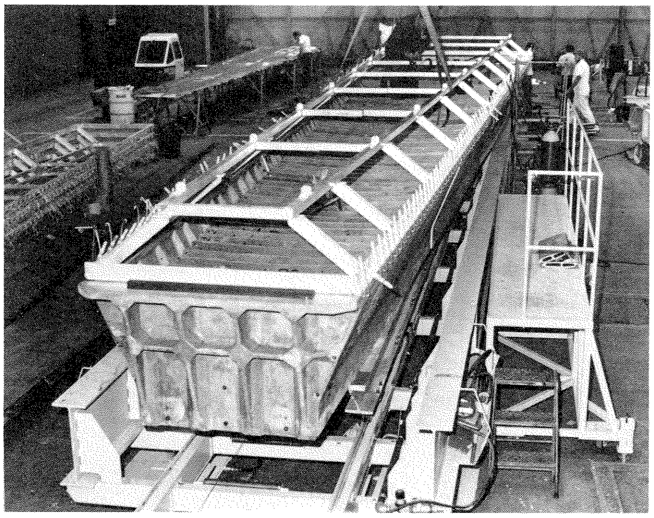


Figure 4: A 15m age-forming tool for aircraft 'skin' panels.

As with the example of the antenna, the deformation survey of the tool was of relative type. The entire assembly was expected to deform, and it was required that this deformation be measured to an accuracy of under a millimeter. A pre-analysis of the planned photogrammetric network indicated that the design demonstrated a sufficient level of sensitivity to detect deformations of a half millimeter or so.

At each epoch of measurement, mean object point coordinate standard errors of 0.25mm were obtained. This level of precision corresponded to a proportional accuracy of just over 1 part in 60,000. In view of the fact that the client sought only 1 part in 35,000 one may validly ask if perhaps the network was over-designed, leading to a costlier than necessary measurement. Well, in this case considerations of reliability primarily governed the network design. The error propagation carried out at the network planning stage demonstrated the need for a minimum of 4-photo coverage on the top and sides of the tool. As a consequence of enhancing the reliability by providing this coverage the level of accuracy and sensitivity were also markedly improved.

An analysis of the point movements, after transformation of the coordinates from the two epochs of measurement into a common reference system (again based on all points since no stable reference was available and a rigorous deformation localization was not sought), indicated that the tool had both been twisted and laterally compressed as a result of the age forming process. The compression at the midpoints of the sides was particularly pronounced; a number of points were displaced by upwards of 4mm. As a result of the photogrammetric measurements it was also possible to ascertain growth rates in the tool and skin panel and compare these to theoretically modelled values. On the subject of thermal influences, it is interesting to note that most of the standard self-adhesive backed retrotargets survived the autoclave temperatures of 200 °C. Those that were damaged were precisely replaced prior to photography for the second epoch.

Large Process Compressor

The final deformation measurement project considered was the most complex and difficult of the four discussed. The structure measured was a large three-stage, four-cylinder hydrogen compressor located in a chemical plant. The aim of the project was to determine thermally induced deformations of the compressor to an accuracy of better than 0.2mm. Deformations were to be quantified by first measuring a network of points when the compressor was 'cold' (not running), and then measuring the same network when the unit was in its 'hot' running state. A detailed account of the project has been reported in FRASER (1985). Here, aspects related to the photogrammetric network design and the analysis of deformations will be reviewed.

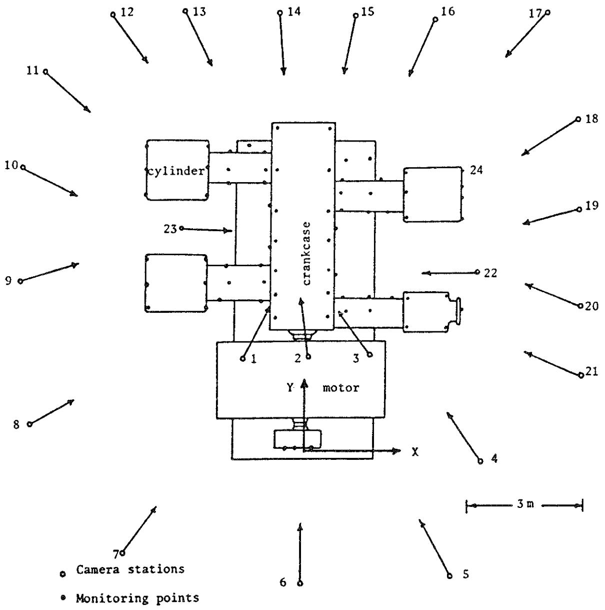


Figure 5: Camera station geometry for process compressor measurement.

The layout of the compressor, which covered a floor area of approximately 8m by 10m and extended to a height of 3m, is illustrated in Figure 5. One of the chief maintenance concerns for the compressor centers on alignment. Departures from true alignment in the cylinders, crosshead guides (the connection between cylinders and crankcase) and crankcase can cause excessive wear in the compression cylinders and this can lead to the necessity for very expensive, earlier-than-scheduled maintenance. Initial alignment takes place when the compressor is in its 'cold' state, yet as a result of thermal loading deformation occurs in the transition from the 'cold' to the 'hot' running state.

At the outset it was unclear as to whether the deformation measurement would be of relative or absolute type. Alignment changes were to be determined with respect to the crankcase, but the stability of crankcase housing was unknown, although it was not expected to deform to a significant degree. The deformation analysis approach applicable to absolute networks was adopted, with some reservations regarding the stability of the set of reference points on the top of the crankcase housing (some were mounted on adjoining plates such that uniform heating would cause pairs of points to move in different directions).

In planning the photogrammetric networks one crucial fact had to be taken into account: the compressor vibrated significantly when running, and the amplitude of the vibration at points on the cylinder heads was larger than the anticipated thermally induced displacements that were to be measured. The vibration problem was overcome by using a multiple stroboscopic flash approach at each camera station (see FRASER, 1985). Compounding the vibration problem was the complex shape of the compressor and the awkward positions in which monitoring points were required. Precisely spherical steel spheres, epoxied in countersinks in the compressor, served as monitoring targets. The use of planar targets was precluded because most points were required to be imaged from a wide range of directions.

The imaging geometry adopted for the 'cold' and 'hot' measurements of the compressor is shown in Figure 5. Some 23 camera positions were required to provide a network of sufficient geometric strength and sensitivity. About five of these camera stations were needed simply to tie in the three points on the crankshaft support which were not intervisible with the rest of the compressor due to the motor housing. In each network approximately 100 targets were to be triangulated, 67 of these being monitoring points and 30 being temporary 'tie points' which were removed following each measurement. Pre-analysis of the photogrammetric network revealed that a mean positional standard error of 0.1mm could be anticipated. The design precision was by no means homogeneous, however, with coordinate standard errors ranging from 0.04mm for points on the crankcase housing to 0.25mm for a few targets with unavoidably poor geometry.

Considerations of photographic coverage, coupled with depth-of-field limitations, necessitated the use of the large format CRC-1 camera with a wide-angle lens of 120mm focal length. Photography was secured initially for the 'cold' state and then one week later for the 'hot' state. In the subsequent data reduction mean positional standard errors of 0.11mm and 0.10mm were obtained for the measurements at each monitoring epoch.

Overall, the results represented in each case a positioning accuracy of better than 1 part in 85,000 of the compressor's principal dimension. For points atop the crankcase housing, which were 'seen' in up to 16 photographs, the accuracies approached 1 part in 240,000.

The analysis of deformation commenced with an examination of the stability of points on the crankcase housing. It was found that while significant point movements had occurred a subset of six reference points exhibited sufficient relative stability. These six points then formed the absolute reference points for the localization of point movements, and both sets of coordinates were transformed into this common datum. Point displacements were then computed from coordinate differences. Deformations at the 67 monitoring points ranged from a displacement of 2.5mm at point 24 (see Figure 5) down to non-significant movements of less than 0.2mm. In computing the magnitude of displacement vectors the effect of uniform heating of the compressor was first subtracted. In general, point movements were at the 0.8 to 1.2mm level, and thus were clearly statistically significant at the 95% confidence level. Plots of the measured deformation indicated consistent trends especially in changes of the alignment of cylinder heads with respect to both the crosshead guides and the axis of the crankshaft. With the number of monitoring points established it was possible to build up a reasonably comprehensive picture of the three-dimensional pattern of thermally induced deformations in the compressor.

CONCLUDING REMARKS

The four measurements considered are representative examples of how industrial photogrammetry can be applied to monitoring structural deformation. As a final note, it is useful to reflect on advantages of photogrammetry which are not necessarily shared by other monitoring techniques: the data acquisition is rapid and non-contact, the density of the target array does not impact on the data acquisition time, with an automatic monocomparator the measurement is often faster than the alternative optical triangulation technique of digital theodolites, and point measurements can be made to high and homogeneous accuracies.

REFERENCES

COOPER, M.A.R., 1984. Deformation Measurement by Photogrammetry. Photogrammetric Record, 11 (63):291-301.

FRASER, C. S., 1983. Photogrammetric Monitoring of Turtle Mountain: A Feasibility Study. Photogrammetric Eng. & Remote Sensing, 49 (11): 1551-1559.

FRASER, C. S., 1985. Photogrammetric Measurement of Thermal Deformation of a Large Process Compressor. Photogrammetric Eng. & Remote Sensing, 51 (10): 1569-1575.

FRASER, C. S., 1986. Microwave Antenna Measurement by Photogrammetry. Photogrammetric Eng. & Remote Sensing (In Press).

FRASER, C. S. and D. C. BROWN, 1986. Industrial Photogrammetry: New Developments and Recent Applications. Photogrammetric Record (In Press).

FRASER, C. S. and L. GRUENDIG, 1985. The Analysis of Photogrammetric Deformation Measurements on Turtle Mountain. Photogrammetric Eng. & Remote Sensing, 51 (2): 207-216.

HECK, B., 1982. Report of the FIG Working Group on the Analysis of Deformation Measurements. Presented to the FIG Comm. 6 Meeting, Budapest.

NIEMEIER, W., 1981. Statistical Tests for Detecting Movements in Repeatedly Measured Geodetic Networks. Tectonophysics, 71: 335-351.

NIEMEIER, W., 1982. Design, Diagnosis and Optimization of Monitoring Networks in Engineering Surveying. Presented Paper, The Centennial Convention of CIS, Ottawa, April.

PELZER, H., 1971. Zur Analyse geodatischer Deformation smessungen. Deutsche Geod. Komm., Series C, No. 164, Munich.

PELZER, H., 1972. Nachweis von Staumauerdeformationen unter Anwendung statistischer Verfahren. Berichte Arbeitsgruppe B, Deutscher Geodatentag, Braunschweig.